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A Case Study on Incorporation of Ageing Effects into the PSA Model

EC JRC Network on Use of Probabilistic Safety Assessments (PSA) for Evaluation of Aging Effects to the Safety of Energy Facilities.
Task 7.

A. Rodionov

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Abstract

This report presents the results of a case study on incorporation of ageing effects into the PSA model and discussions on the use of PSA to evaluate the SSC ageing effect on overall plant safety. The study was carried out within the framework of the EC-JRC Ageing PSA Network Task 7.
The possible impact of age-related degradation on the component reliability and on the plant risk profile is demonstrated using the PWR Large LOCA PSA model as an example. Practical insights, recommendations and limitations are also discussed.

Key Words: ageing effects, Probabilistic Safety Assessment, time-dependent reliability model.

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1. Introduction

The initial rationale behind the Network on the Use of Probabilistic Safety Assessment (PSA) for the Evaluation of Ageing Effects on the Safety of Energy Facilities (Ageing PSA) was that current standard PSA tools do not adequately address important ageing issues, which could have a significant impact on the conclusions drawn from PSA studies and applications where plants are operated at an advanced age or long-term.

For example:

- reliability models for components are based on the “component constant failure rate” assumption, which may not be valid in the long term;
- the reliability data used in PSAs may not adequately represent the current status of plants, because the data was mostly collected during PSA development; it might reflect the situation at the beginning of operation, but equipment reliability could deteriorate with time;
- existing PSAs traditionally overlook some components (e.g. cables, structures, etc.) as having a very low probability of failure, but this probability can increase with the age of the unit.

The knowledge resulting from the Ageing PSA Network should help PSA developers and users:

- to incorporate the effects of equipment ageing into current PSA tools and models,
- where PSA cannot be applied (where there are no or inadequate probabilistic ageing models or a lack of data, etc.), to specify and prioritize reliability monitoring approaches to ensure that any decrease in the reliability of SSC is identified and corrected in time,
- to promote the use of PSA for ageing management and risk-informed application for nuclear power plants.

This study is prepared in the frame of Task 7 “Incorporation of Age depended reliability parameters and data into PSA model” of Ageing PSA Network activities [1].

Task 7 is aimed to demonstrate a practical approach and technique to introduce of SSCs ageing effect to the existed PSA model.

It is expected that the results of this task will help

- to propose appropriate and practical approach for incorporation of ageing effects to the PSA model,
- to identify main issues and limitations related to the demonstration of ageing impact to the risk on different levels (component, system, overall plant),
- to evaluate the needs for modifications in PSA software codes.

Previously performed Ageing PSA Network Case Studies on time-dependent reliability analysis [2, 3] identified the types of initial reliability data and the procedure to construct age-dependent reliability models and estimate the reliability parameters for PSA components. These results were applied for preparation of input reliability data set.

2. Task specification

The ageing could affect the reliability of one or more SSCs. In case of sufficient reliability data, age-dependent reliability models could be constructed and introduced into the PSA.
For active components, the age-dependent reliability parameters could be considered at the level of the fault trees by assigning time-dependent unavailabilities for corresponding basic events in the fault trees.
The fault trees could be used in the calculation of the probability of functional events, as well as for estimation of initiating event frequencies. In general, both of the cases have to be considered in the input parameter specification.
In addition, SSCs and failure modes potentially important from ageing point of view can be divided in two categories:

- sensitive to ageing effects components and failure modes not included in a reference PSA model. In this case, some changes in the fault/event trees structure, creation of new basic events, as well as elaboration of time-dependent reliability parameters are needed;
- components and failure modes modelled in PSA. In this instance, changes can be made to reliability parameters for basic events.

Depending on the available PSA code and the expected applications, the technique for introducing time-dependent unavailability at the level of basic events could be different.
In RiskSpectrum, which is used in many European countries, there is no possibility to specify basic event unavailability as a function of time, and then to perform a risk analysis of the entire model at different time points.
The objective of the present study is to propose and to demonstrate the applicability of the approach how to integrate time-dependent reliability parameters into PSA and calculate the impact of ageing on the risk profile as a function of the unit age.
This objective is reached by implementing of following tasks :

- choose and describe the reference model,
- develop the procedure for consideration of ageing effects into PSA,
- preparing the input parameters data set,
- demonstration of ageing impact to risk and reliability (on the level of system unavailability and core damage frequency),
- evaluation of ageing impact to the “decisive” risk indicators (risk profile, contributions, risk importance measures, etc.)
- sensitivity and uncertainty analysis.

The following chapters present the results of the tasks and related discussion.

3. Reference model

A three-loop PWR PSA model for a Large LOCA initiating event was considered as a reference model. The model consists of 4 Event Trees (see Fig. 1-2) developed taking into account the following factors :

- operational state : full power operation (PO) and hot shutdown (HD),
- brake location : hot leg (HL) or cold leg (CL).

All Event Trees have the same structure.

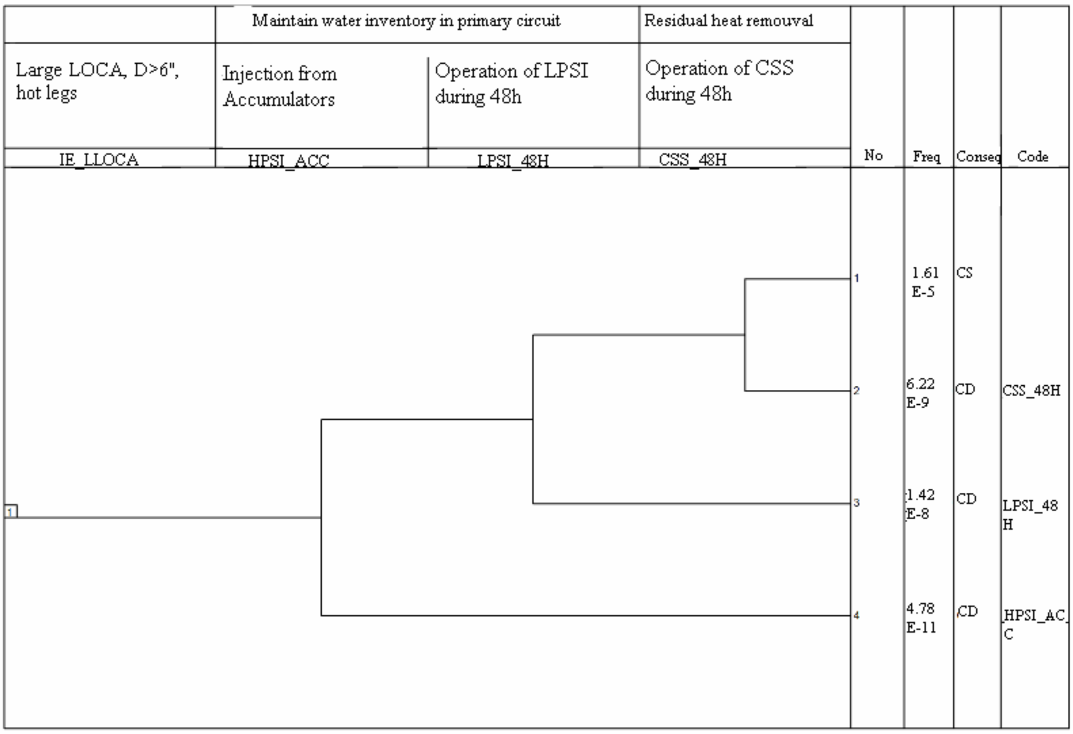

Figure 1.

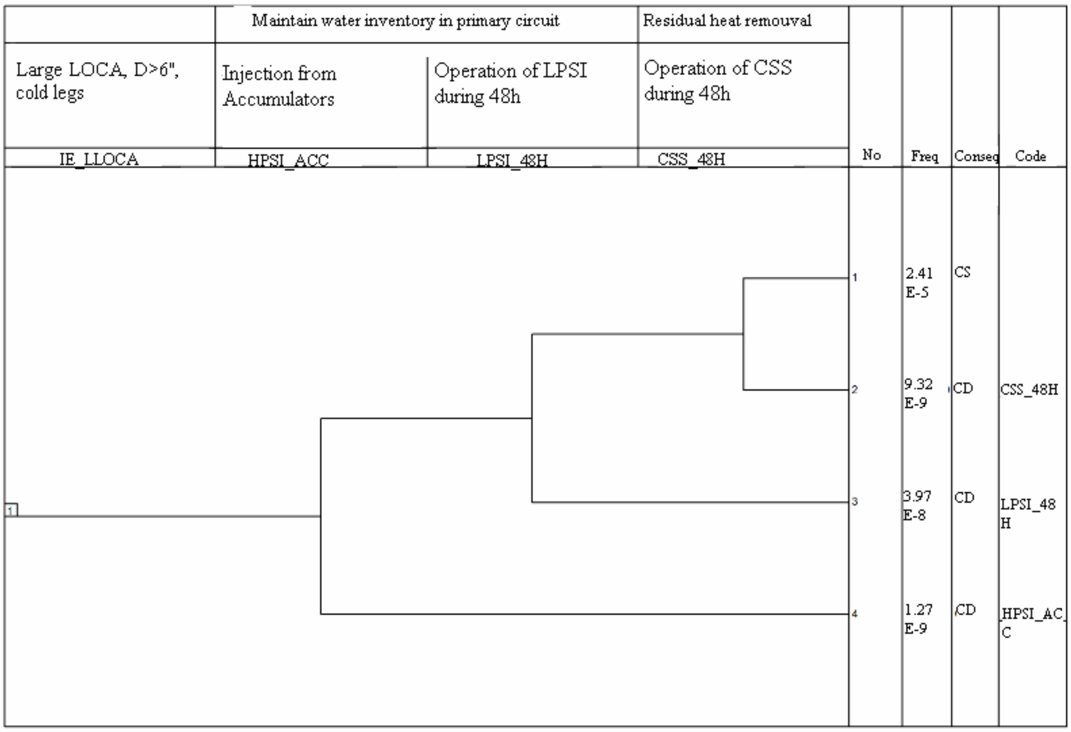

Figure 2.

Table 1 presents the results of CDF calculations.

Table 1

IE	IE ID	IE frequency	CDF	%
Large LOCA from the hot leg when reactor is on power operation	LLOCA PO/HL	1.61E-05	2.05E-08	29%
Large LOCA from the cold leg when reactor is on power operation	LLOCA PO/CL	2.41E-05	5.03E-08	70%
Large LOCA from the hot leg when reactor is on hot shutdown state	LLOCA HS/HL	1.79E-07	3.34E-10	>0.5%
Large LOCA from the cold leg when reactor is on hot shutdown state	LLOCA HS/CL	2.68E-07	7.21E-10	1%
Total		4.06E-5	7.18E-8	

Figure 3 provides the risk distribution considering the brake location and operating state.

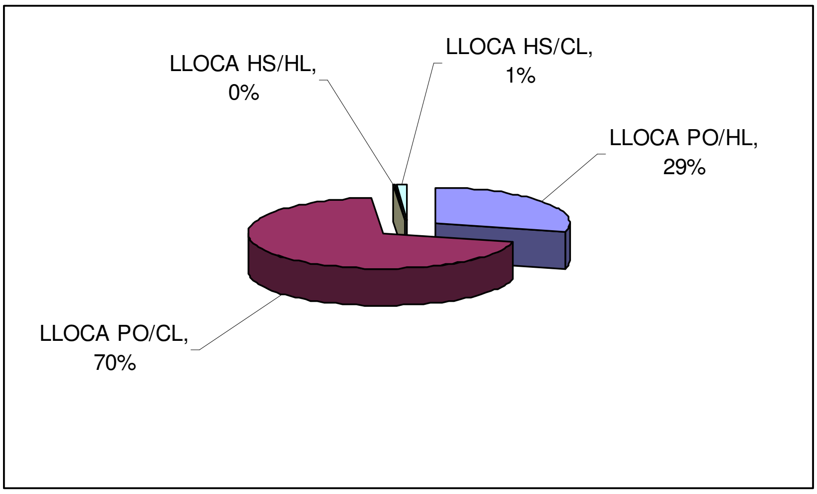

Figure 3.

More detailed results for the reference model, including accident sequences calculations, MCS and importance measures are presented in Annexe 1.

In order to demonstrate the impact of ageing effects on the system level the Containment Spray System (CSS) was considered, see Fig.4. In case of Large LOCA the CSS assures the residual heat removal from the reactor core. This safety function is considered in all Event Trees selected for the study. The Fault Tree of CSS is presented in Annexe 2.

Calculated system unavailability value is equal to Qt = 8 10-4, the main contributors are :

- probability of Common Cause Failures (CCF) of RWST level sensors (30%),
- pre-accidental Human Error Probability (HEP) to set-up the I&C relays in a control system which switches the CSS pumps from RWST to containment sump suction line (19%),
- probability to fail to run of the CSS pumps (10%),

- CCF probability of fail to open of Motor Operated Valves (MOV) V13 and V14 (5%).

The detailed results of quantitative analysis of CSS are presented in Annexe 3.

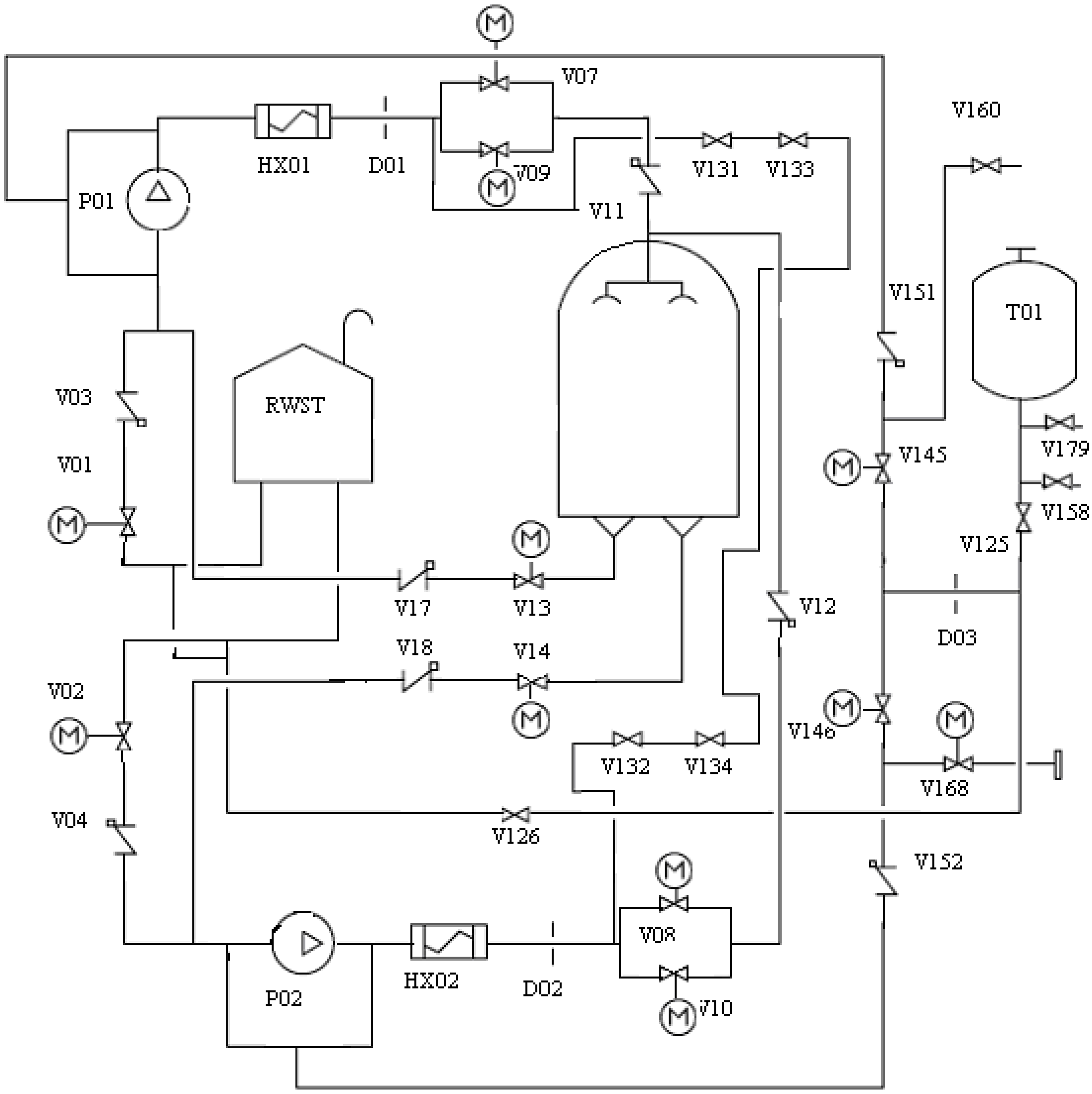

Figure 4.

4. Procedure for consideration of ageing effects into PSA

To integrate time-dependent reliability parameters into PSA and calculate the impact of ageing on the risk profile as a function of the unit age, it was proposed to use CDF as averaged at one-year intervals calculated for different age points, for example for 10, 20, 30 and 40 years of operation. This provides the same notation of risk as in a standard PSA and makes it possible to compare the results with the reference values.

To do that for each particular component and failure mode, a set of reliability parameters has to be calculated using time-dependent reliability models. This set consists of parameter values (averaged at one-year intervals) estimated for considered age points, see Figure 5.

The average value is calculated as :

$$\lambda_{av} = \frac{1}{(t_{i+1} - t_i)} \int_{t_i}^{t_{i+1}} \lambda(t)dt$$

This approach permits to use for basic events the same options and types of reliability models as in the reference PSA. The CDF and risk profile can then be quantified at each point.

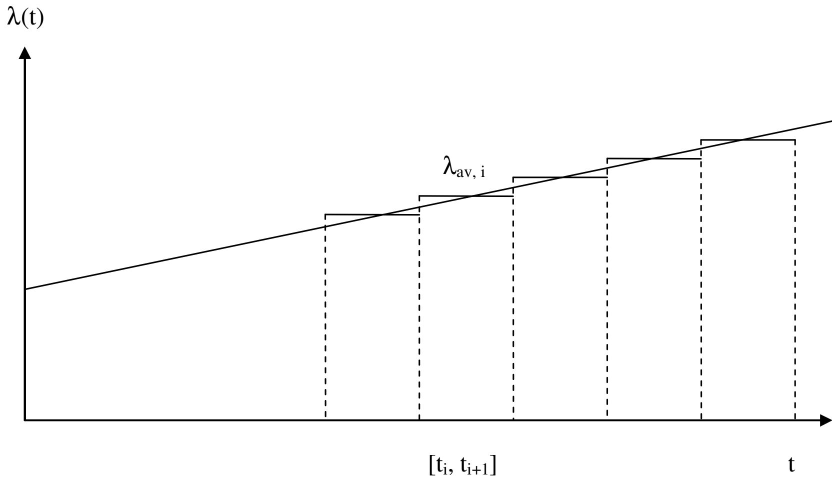

Figure 5.

A procedure to modify the existed PSA reference model consist of several steps [4] :

1) identification the BEs which correspond to the components sensitive to ageing (for which time-dependent reliability models were elaborated);

2) creation of House Events (HE) to trigger the analysis cases and activate the exchange events for each particular time point where the CDF calculation has to be done (for present Case Study : 10, 20 ,30 and 40 years of operation);

3) for each BE identified on the step 1, fore exchange events were specified. Each exchange event correspond to the component unavailability at the time point 10, 20, 30 and 40 years in operation and it's linked to the corresponded HE;

4) specification of attributes for created exchange events taking into account failure mode, operating state, unit age considered for calculation, test and maintenance strategy, type and parameters of reliability model;

5) creation of the parameters (failure rate and probability), linking them to the exchange events and input the initial values for the point estimations and distribution functions;

6) in case when initial BE is considered for the CCF group, for each exchange event the correspondent CCF group was created. The CCF model parameters (e.g. β-factors) remain the same in the CCF group modelling. CCF failure probability, then, changed with the unit age proportionally to the changes in a probability of independent failure;

7) as soon as all modifications made for all identified components and BEs, the CDF could be quantified for particular time point. For this, fore Analysis Cases were specified. For each analysis case in a Boundary Condition Set specification the corresponded House Event was set up to “true”.

Depending of the purpose of the calculation the following risk measures could be quantified :

- CDF changing as a function of unit age,
- modification of risk profile (contribution of IE groups to the CDF) as a function of unit age,
- modification of the list of the dominant MCS,
- changing of risk importance measures (Risk Increasing Factor, Risk Decreasing Factor, etc.).

5. Input parameters data set

The set of "virtual" reliability data was prepared on the basis of the results of case studies [3], available generic data sources [5, 6, 7] and expert opinions. The data includes time-dependent reliability models for certain mechanical, electrical and I&C components of Low Pressure Safety Injection (LPSI) and Containment Spray (CSS) Systems, see Annexe 4.

For most components, the relative increase in failure rate (probability) is not so significant (see example in Fig. 6). A strong ageing impact was considered for one component type — pump motors (see Fig. 7). In this instance, for the best fitted log-linear model (p-value = 0.98), the relative increase in failure probability is more than three orders of magnitude towards the end of the design lifetime. At the same time, the Weibull model, which fits with a significance level of 0.96, gives a relative increase by a factor of 20 towards the end of the design lifetime.

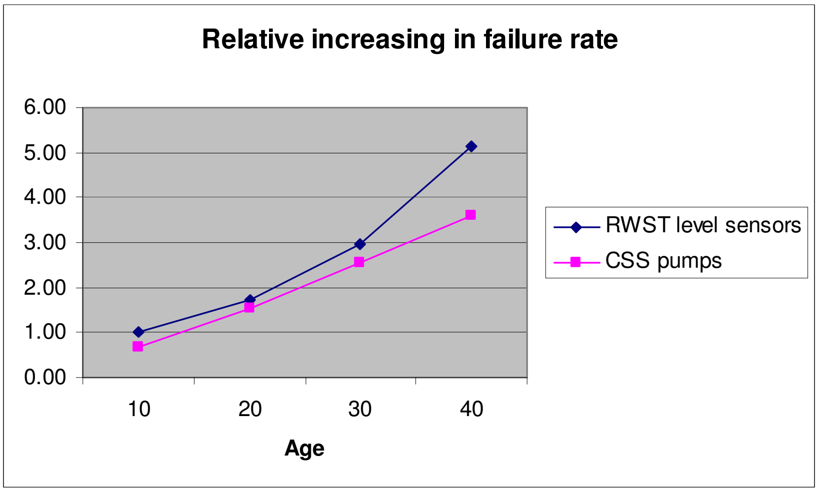

Figure 6.

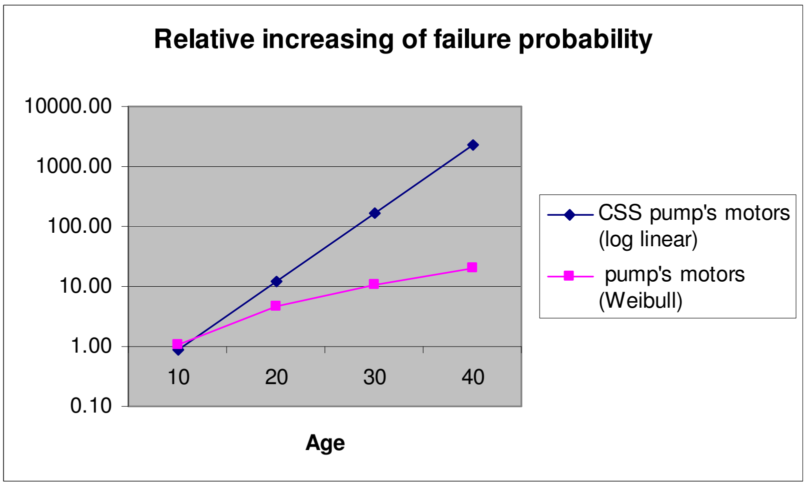

Figure 7.

"As bad as old" preventive maintenance was considered in all cases.

Quantification has been calculated for a reference value (no ageing effects considered) and age points of 10, 20, 30 and 40 years.

6. System Level Effect

The results of calculations performed for the CSS Fault Tree show that system unavailability increases with time by more than one order of magnitude with regard to the reference value (see Fig. 8). Up to the age of 30 years, the main contributor to unavailability (Fig. 9) is failure in the level sensors in the RWST, which provides a signal to switch the CSS to containment sump recirculation. But at the age of 40 the dominant impact on system unavailability is failure of the CSS pump motors. Thus, a rapid and sharp increase in unavailability due to the pump motors can be explained by the choice of the log-linear model for the failure rate. As mentioned in Ch.5, this model provides more conservative extrapolation results.

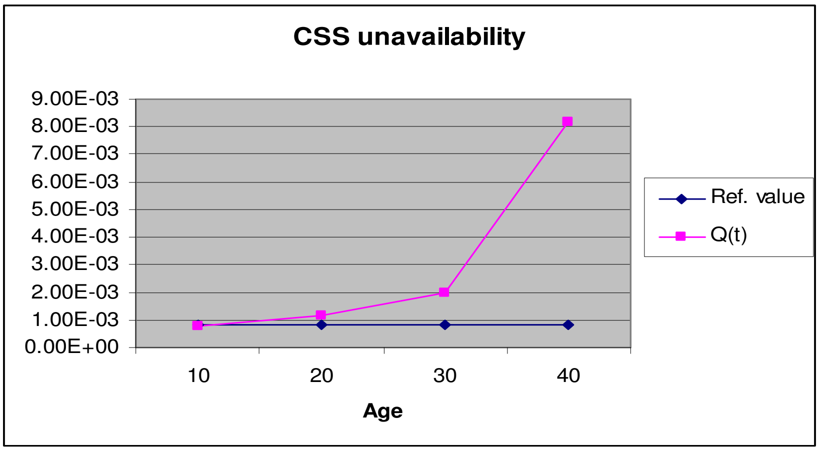

Figure 8.

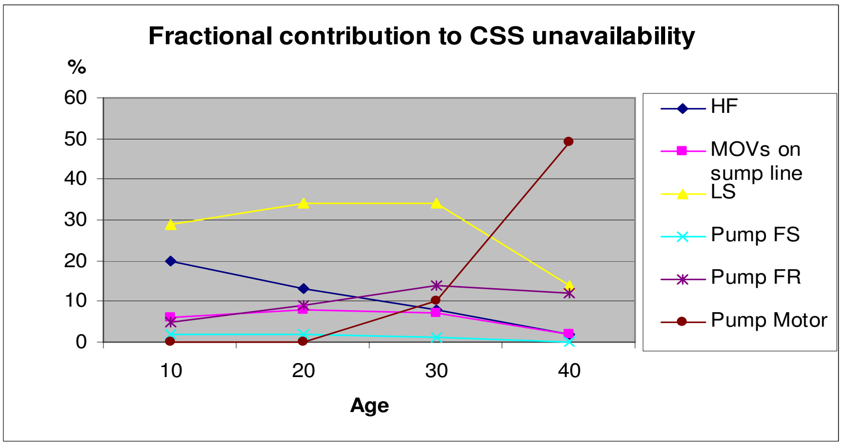

Figure 9.

For comparison purposes, two contributors with constant failure probability are presented in Fig. 9 : human error (20% fractional contribution to the reference value) and CSS pumps fail to start (2% contribution to the reference value). As can be seen from the graph, their contribution to total system unavailability gradually decreases with time.

Annexe 5 presents the detailed information on changing in MCS list, fractional contributions and other importance measures calculated for the CSS.

7. Plant Level Effect

Table 2 summarize the results of calculations for Large LOCA initiating events carried out with RiskSpectrum. Fig. 10 presents the impact of ageing on CDF. The result of risk extrapolation is an increase in CDF from 6.58 10-8 at 10 years to 6.19 10-7 at 40 years. In comparison with the reference value (7.18 10-8) the increase is by a factor of 8.6 by the end of the designed lifetime.

Once the components most sensitive to ageing (LPSI and CSS pump motors and level sensors) are in the Minimal Cut Sets of dominant sequences, the relative contribution of the sequences to the total risk of Large LOCA remains approximately the same with age. The same picture can be seen for contributions to the risk associated with the different reactor states and location of the pipe break.

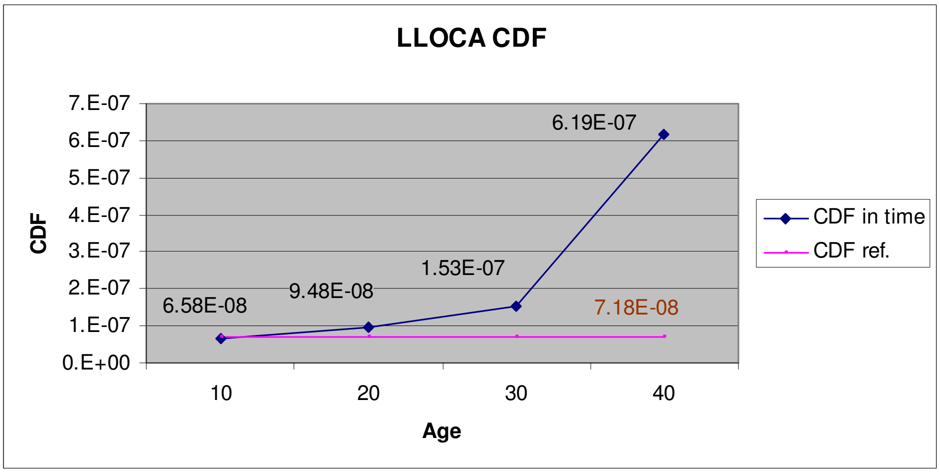

Figure 10.

Figure 11 presents the results of the sensitivity analysis of the reliability model chosen for the most sensitive components, i.e. pump motors. For this component in the base case, the log-linear model was considered. As mentioned in Ch.5 (see Fig. 7), the Weibull model provides quite different values for extrapolation of failure probability to the end of the design lifetime than the sensitivity analysis.

The generic conclusion from this analysis is the need to examine the accuracy of several model alternatives before applying one to PSA.

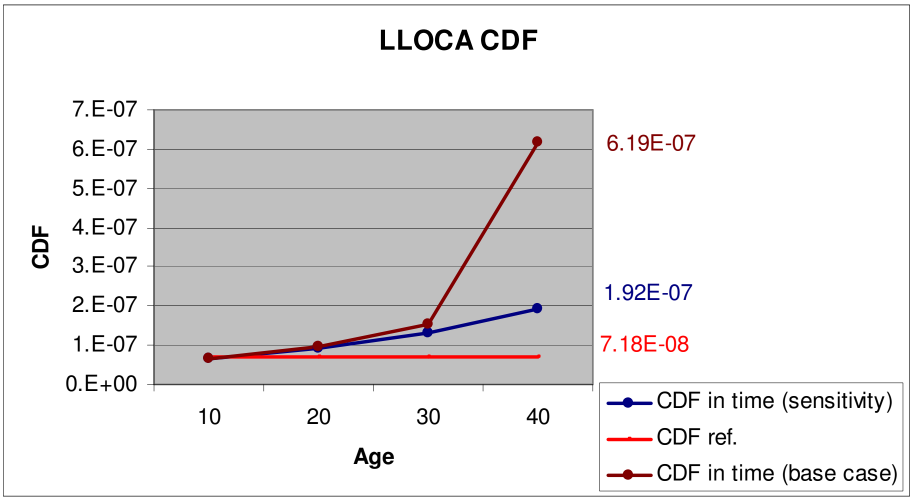

Figure 11.

Table 2

IE ID	IE frequency	AS №	CDF (reference value)	CDF as a function of time				% contribution to the total of ET (CDF(40))	% contribution to the total CDF of LLOCA (CDF(40))
				10 years	20 years	30 years	40 years		
LLOCA PO/HL	1.61E-05	2	6.22E-09	5.65E-09	9.20E-09	1.74E-08	1.07E-07	45%	17%
		3	1.42E-08	1.24E-08	2.02E-08	3.49E-08	1.29E-07	55%	21%
		4	4.78E-11	4.78E-11	4.78E-11	4.78E-11	4.78E-11	0%	
		Total ET	2.05E-08	1.81E-08	2.94E-08	5.23E-08	2.36E-07		
LLOCA PO/CL	2.41E-05	2	9.32E-09	8.47E-09	1.38E-08	2.61E-08	1.60E-07	43%	26%
		3	3.97E-08	3.70E-08	4.89E-08	7.13E-08	2.14E-07	57%	35%
		4	1.27E-09	1.27E-09	1.27E-09	1.27E-09	1.27E-09	0%	
		Total ET	Total ET	4.67E-08	6.40E-08	9.87E-08	3.75E-07		
LLOCA HS/HL	1.79E-07	2	6.89E-11	6.27E-11	1.02E-10	1.93E-10	1.19E-09	43%	
		3	2.65E-10	2.42E-10	3.46E-10	5.23E-10	1.59E-09	57%	
		4	5.33E-13	5.33E-13	5.33E-13	5.33E-13	5.33E-13	0%	
		Total ET	3.34E-10	3.05E-10	4.49E-10	7.17E-10	2.78E-09		
LLOCA	2.68E-07	2	1.03E-10	9.39E-11	1.53E-10	2.89E-10	1.78E-09	40%	

HS/CL		3	6.04E-10	5.68E-10	7.27E-10	9.96E-10	2.61E-09	59%	
		4	1.42E-11	1.42E-11	1.42E-11	1.42E-11	1.42E-11	0%	
		Total ET	7.21E-10	6.76E-10	8.94E-10	1.30E-09	4.40E-09		
Total CDF for LLOCA			7.18E-08	6.58E-08	9.48E-08	1.53E-07	6.19E-07		

For the base case an analysis of risk importance measures was performed. Fig. 12 shows the variation of Fussell-Vesely Importance for the main contributors to CDF. The nature of the curves is about the same as for the Fractional Contribution of the failure of a particular component to system unavailability shown in Fig. 9.

For components not sensitive to ageing, the Fussell-Vesely Importance monotonically decreases with time (see LPSI valves or HE on RWST sensors). For components sensitive to ageing, the behaviour of the measure could differ according to rate of ageing (see, for example, LPSI pumps and CSS pump motors). In this example, the most dramatic changes in component importance take place between 30 and 40 years for the most sensitive components.

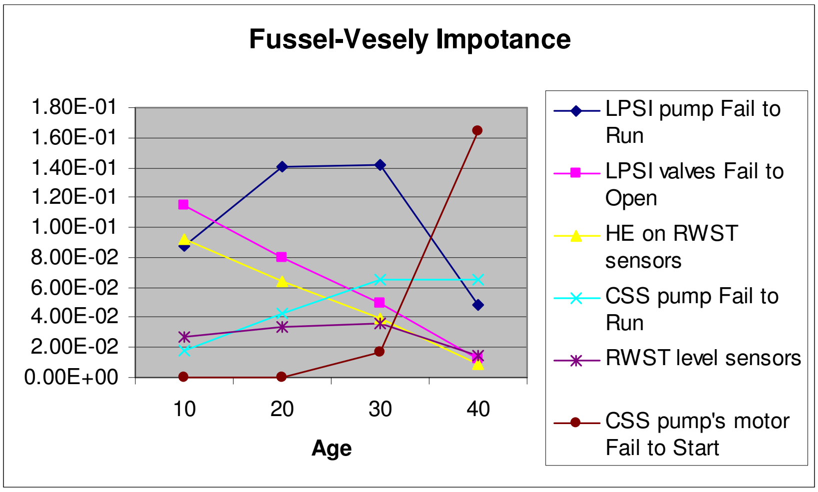

Figure 12.

The Risk Increasing Factor monotonically decreases with time for all the main contributors to CDF (see example of LPSI valves (not sensitive to ageing) and CSS pump motors (very sensitive to ageing) – Fig. 13). However, the most sensitive components remain the same. This behaviour makes the Risk Importance Factor less informative from a decision-making point of view.

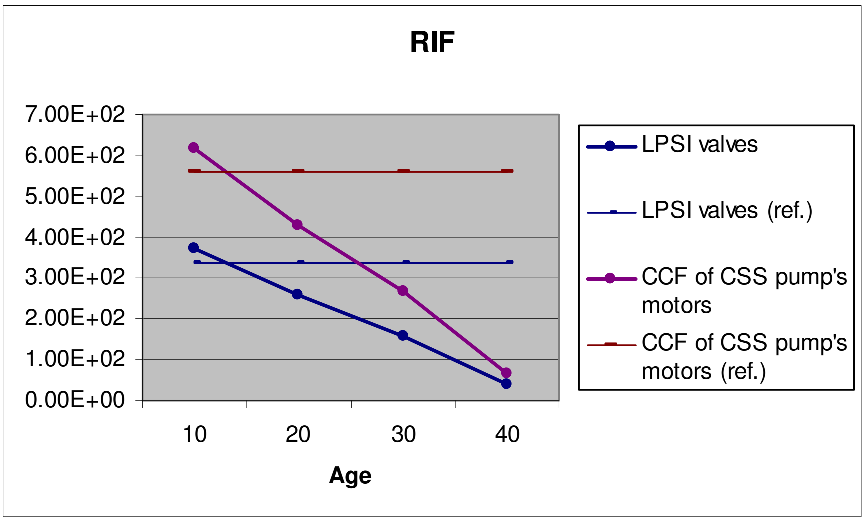

Figure 13.

The basic conclusion is that ageing can alter the risk importance values for particular components and failure modes. This has to be taken into account when applying these measures for component prioritization (for operation or maintenance optimization).

The detailed information on risk profile, changing in MCS list, risk importance measures calculated for the BEs and components is presented in Annexe 6.

8. Uncertainty analysis

The methods for time-dependent reliability model selection and parameters estimation proposed in [3] permit to evaluate associated stochastic uncertainties both for interpolation and extrapolation of the failure intensity function (i.e. predictive estimations).

It has to be pointed out that the procedure for model selection includes the goodness of fit test which compare the fitness (to existed data) of proposed time-dependent models versus the fitness of constant failure rate model. The maximum p-value is used as a criteria to choose the best fitted model. From this point of view, for all components identified as sensitive to ageing (see Annexe 4) selected time-dependent models better interpolate the data, that constant model does.

The uncertainties associated with predictive extrapolations were characterized by Error Factors estimated in each time point as :

$$EF = \sqrt{\lambda_{95\%} / \lambda_{5\%}}$$

where $\lambda_{95\%}$ and $\lambda_{5\%}$ are the upper and lower bounds of 90% confidence interval for failure rate intensity estimation at the correspondent time point.

Then, for each reliability parameter associated with time-dependent analysis case in RiskSpectrum model, the log-normal distribution and EF were specified to proceed with uncertainty analysis.

The results of uncertainty analysis for Large LOCA CDF are presented on Fig. 14. Here the CDF point estimation and 90% confidence intervals are plotted.

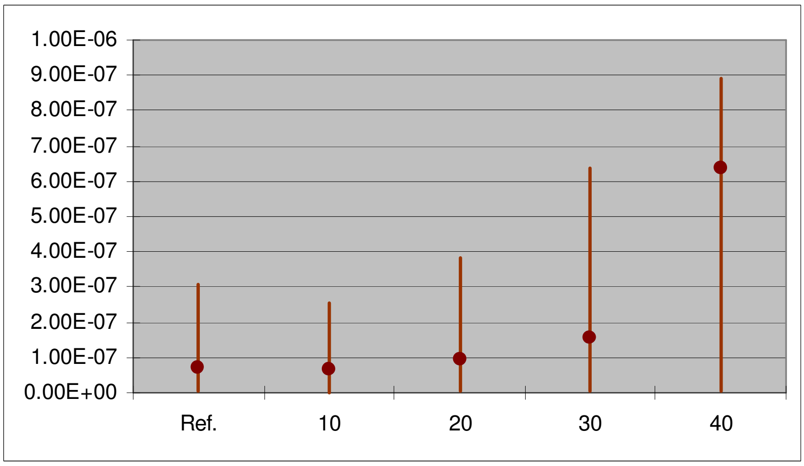

Figure 14 :

As it could be expected the uncertainty of predictive extrapolations are increasing with time. The upper bound of 90% confidence interval increases from the value of 2.55 10^{-7} at 10 years, up to 8.92 10^{-7} for the 40 years of operation, i.e. with the factor of 3.5. This increasing seems to be not so dramatic, when comparing it with the increasing of CDF mean value for the same period of time, which is up to the factor 9.4. But looking to the difference between obtained mean (6.39 10^{-7}) and median (6.28 10^{-8}) values at the time point of 40 years, it could be concluded that the mean value estimation is not so reliable.

The uncertainty analysis was done for the sensitivity study described in Ch.7. The results are presented at the Fig. 15. It could be conclude that the application of alternative time-dependent reliability model (Weibull instead of log-linear) for particular component group does not affect too much to the uncertainties of the whole model.

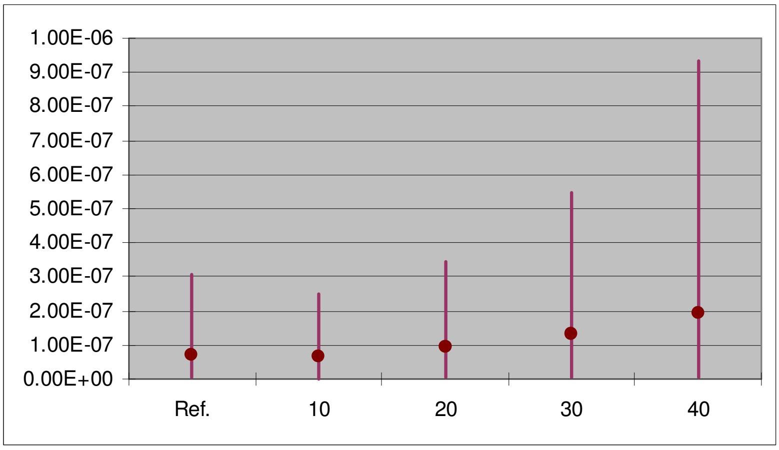

Figure 15

Detailed results of uncertainty analysis are presented in Annexe 7.

9. Conclusions

Ageing effects can alter the conclusions of reference PSA studies. In particular, they can impact on

- system unavailability and CDF,
- dominant accident sequences and contributors to CDF,
- component risk importance measures.

Considering ageing effects in PSA and reliability analysis can help in the selection and prioritization of SSCs and in ageing management and maintenance measures as part of a risk-informed decision-making process.

The main problems relate to methodology, data and resource availability.

The purpose of the EC-JRC Ageing PSA Network's activities is to provide PSA engineers with practical approaches, methods and advice on how evaluate the importance of ageing issues by means of PSA modeling. The results presented demonstrate methods and approaches proposed for the selection of SSCs susceptible to ageing, the development of time-dependent reliability models and the evaluation of ageing effects on overall plant safety by extrapolation of reliability parameters.

References

1. D(07)5504 from 5 of March 2007. Meeting Minutes “EC JRC Aging PSA Network Steering Committee meeting. 20 February 2007, Amsterdam, Netherlands.”

2. C. Atwood, O. Cronval, M. Patrik, A. Rodionov. Models and data used for assessing the ageing of systems, structures and components. EUR 22483 EN. DG JRC Institute for Energy, Petten, Netherlands, 2007.

3. A. Antonov, V. Chepurko, A. Polyakov, A. Rodionov. A Case Study on Investigation of Component Age Dependent Reliability Models. EUR 23079 EN. DG JRC Institute for Energy, Petten, Netherlands, 2007.

4. A. Rodionov, D. Kelly, J.-U. Klugel. Guidelines for Analysis of Data Related to Aging of Nuclear Power Plant Components and Systems. EUR xxx EN. EC DG JRC Institute for Energy, Petten, Netherlands, 2009.

5. H. Wels. Generic ageing characteristics of conventional power plants. Lessons learned from data-analysis a model for life extension planning. NRG Report 911569/07.81244/C, Arnhem, Netherlands, February 2007.

6. Proritization of TIRGALEX – recommended components for further aging research. NUREG/CR-5248. US NRS, USA, 1988.

7. A.Lannoy, H.Procaccia. Evaluation et maitrise du vieillissement industriel. Lavoisier, Paris, France, 2005.

Annexe 1 : Large LOCA reference model results (accident sequences CDF, MCS and importance measures)

Table A1-1.

IE ID	IE frequency	AS №	CDF	% in ET	% in total CDF
LLOCA PO/HL	1.61E-05	2	6.22E-09	30%	
		3	**1.42E-08**	**69%**	20%
		4	4.78E-11	0%	
		Total ET	2.05E-08		
LLOCA PO/CL	2.41E-05	2	9.32E-09	19%	13%
		3	**3.97E-08**	**79%**	**55%**
		4	1.27E-09	3%	
		Total ET	5.03E-08		
LLOCA HS/HL	1.79E-07	2	6.89E-11	21%	
		3	**2.65E-10**	**79%**	
		4	5.33E-13	0%	
		Total ET	3.34E-10		
LLOCA HS/CL	2.68E-07	2	1.03E-10	14%	
		3	**6.04E-10**	**84%**	
		4	1.42E-11	2%	
		Total ET	7.21E-10		

Table A1-2.

ET/AS ID	CDF	%	IE	BE
LLOCA PO/CL / AS3	7.53E-09	10.45	LLOCA_PO_CL	RCP222VP_RO
	7.53E-09	10.45	LLOCA_PO_CL	RCP122VP_RO
	5.14E-09	7.13	LLOCA_PO_CL	RIS2PO#1DF_48H-ALL
	3.62E-09	5.02	LLOCA_PO_CL	FH_RPR4_PTR400XU
LLOCA PO/HL / AS3	3.43E-09	4.76	LLOCA_PO_HL	RIS2PO#1DF_48H-ALL
	2.41E-09	3.35	LLOCA_PO_HL	FH_RPR4_PTR400XU
LLOCA PO/CL / AS2	1.11E-09	1.54	LLOCA_PO_CL	C4PTR4MN1-123
	1.11E-09	1.54	LLOCA_PO_CL	C4PTR4MN1-124
	1.11E-09	1.54	LLOCA_PO_CL	C4PTR4MN1-ALL
	1.11E-09	1.54	LLOCA_PO_CL	C4PTR4MN1-234
	1.11E-09	1.54	LLOCA_PO_CL	C4PTR4MN1-134
	1.03E-09	1.43	LLOCA_PO_CL	EAS2PO#1DF_48H-ALL
	9.85E-10	1.37	LLOCA_PO_CL	EAS2VBE2RO-ALL

Annexe 2 : Containment Spray System Fault Tree

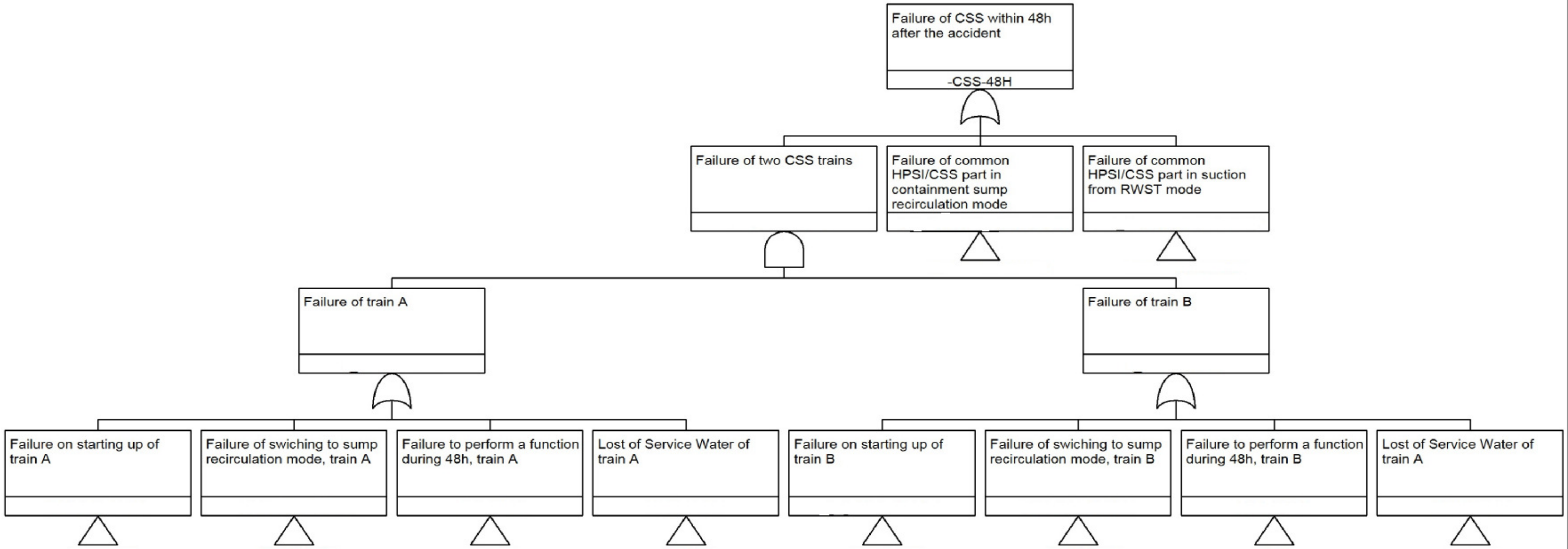

Figure A2.1.

Annexe 3 : CSS quantitative analysis results for reference model

Table A3-1.

№	MCS probability	MCS contribution to Q_t, %	BE 1	BE 2
1	1.50E-04	18.76	HE_I&C	
2	4.59E-05	5.74	CCFRWSTLS1-123	
3	4.59E-05	5.74	CCFRWSTLS1-124	
4	4.59E-05	5.74	CCFRWSTLS1-134	
5	4.59E-05	5.74	CCFRWSTLS1-ALL	
6	4.59E-05	5.74	CCFRWSTLS1-234	
7	4.26E-05	5.33	CSS2PO#1DF_48H-ALL	
8	4.08E-05	5.1	CSS2VBE2RO-ALL	
9	1.78E-05	2.23	CSS001PO_DF_48H	CSS002PO_DF_48H
10	1.75E-05	2.19	CSS2PO#1DS-ALL	
11	1.51E-05	1.89	RPS2CCF3-ALL	
12	1.00E-05	1.25	MC4PUISAR1DSLET	
13	6.63E-06	0.83	CSS4VBE1RO-ALL	
14	6.03E-06	0.75	RPS4CCF2-23	
15	6.03E-06	0.75	RPS4CCF2-13	
16	6.03E-06	0.75	RPS4CCF2-24	
17	6.03E-06	0.75	RPS4CCF2-14	
18	5.30E-06	0.66	CSS2VBJ2DS-ALL	
19	4.80E-06	0.6	CSS2POJ1DS-ALL	
20	4.56E-06	0.57	CSS2MO61DF_48H-ALL	

Table A3-2.

№	BE	Unavailability	FC	RDF	RIF	Sensitivity
1	HE_I&C	1.50E-04	1.87^{E}-01	1.23E+00	1.25E+03	3.23E+00
2	CSS001PO_DF_48H	4.22E-03	6.16^{E}-02	1.07E+00	1.55E+01	1.65E+00
3	CSS002PO_DF_48H	4.22E-03	5.85^{E}-02	1.06E+00	1.48E+01	1.61E+00
4	CCFRWSTLS1-234	4.59E-05	5.73^{E}-02	1.06E+00	1.25E+03	1.60E+00
5	CCFRWSTLS1-ALL	4.59E-05	5.73^{E}-02	1.06E+00	1.25E+03	1.60E+00
6	CCFRWSTLS1-134	4.59E-05	5.73^{E}-02	1.06E+00	1.25E+03	1.60E+00
7	CCFRWSTLS1-123	4.59E-05	5.73^{E}-02	1.06E+00	1.25E+03	1.60E+00
8	CCFRWSTLS1-124	4.59E-05	5.73^{E}-02	1.06E+00	1.25E+03	1.60E+00
9	CSS2PO#1DF_48H-ALL	4.26E-05	5.33^{E}-02	1.06E+00	1.25E+03	1.55E+00
10	CSS2VBE2RO-ALL	4.08E-05	5.10^{E}-02	1.05E+00	1.25E+03	1.53E+00

Table A3-3.

№	Component	FC	RDF	RIF	Sensitivity
1	RWST019MN	2.36E-01	1.31E+00	1.25E+03	3.97E+00
2	RWST018MN	2.36E-01	1.31E+00	1.25E+03	3.97E+00
3	RWST017MN	2.36E-01	1.31E+00	1.25E+03	3.97E+00
4	RWST020MN	2.36E-01	1.31E+00	1.25E+03	3.97E+00
5	CSS001PO	1.59E-01	1.19E+00	1.25E+03	2.83E+00
6	CSS002PO	1.55E-01	1.18E+00	1.25E+03	2.78E+00
7	CSS013VB	7.65E-02	1.08E+00	1.25E+03	1.81E+00
8	CSS014VB	7.56E-02	1.08E+00	1.25E+03	1.80E+00
9	RPS073UA	2.30E-02	1.02E+00	1.25E+03	1.23E+00
10	RPS073UB	2.28E-02	1.02E+00	1.25E+03	1.23E+00

Annexe 4 : Input reliability data set

Table A4-1.

Component group	Failure rate reference value / EF	Best fitted model	Data correction	λ(10) / EF	λ(20) / EF	λ(30) / EF	λ(40) / EF
Electrical Batteries	2.80E-06 /	linear	burn-in failures excluded	2.72E-06	4.30E-06	5.88E-06	7.46E-06
Flow Sensors (Y)	2.40E-06 / 1.3	Weibull	burn-in failures excluded	2.56E-06 / 1.09	3.66E-06 / 1.22	4.51E-06 / 1.31	5.23E-06 / 1.41
Level Sensors	2.10E-06 / 1.3	log-linear	-	2.10E-06 / 1.21	3.62E-06 / 1.65	6.26E-06 / 2.56	1.08E-05 / 4.02
Level Sensors (Y)	2.10E-06 / 1.3	linear	burn-in failures excluded	1.81E-06 / 1.28	3.47E-06 / 1.43	5.13E-06 / 1.64	6.79E-06 / 1.8
Pressure Sensors	1.40E-06 / 1.3	Weibull	-	1.33E-06 / 1.14	1.64E-06 / 1.29	1.86E-06 / 1.43	2.03E-06 / 1.54
Switchers 380 V (pumps) FF	3.10E-07 / 1.5	Weibull	-	3.03E-07 / 2.11	4.18E-07 / 3.70	5.05E-07 / 5.85	5.78E-07 / 8.22
Switchers 380 V (pumps) FD	8.40E-06 / 10.0	log-linear	burn-in failures excluded	6.45E-06 / 2.23	2.32E-05 / 4.85	8.35E-05 / 24.20	3.00E-04 / 128.53
Switchers 6,6 kV FD	4.80E-05 / 2.1	Weibull		5.54E-05 / 1.88	6.48E-05 / 2.86	7.10E-05 / 3.76	7.57E-05 / 4.6
Pumps Motors 6.6kV FR	1.90E-06 / 1.3	Weibull	burn-in failures excluded	2.04E-06 / 1.47	2.87E-06 / 2.55	3.50E-06 / 3.79	4.04E-06 / 5.06
Pumps Motors 6.6kV FS	1.80E-05 / 2.1	log-linear	-	1.57E-05 / 3.02	2.14E-04 / 19.56	2.94E-03 / 394.8	4.02E-02 / 8402
	1.80E-05 / 2.1	Weibull		1.89E-05 / 2.79	8.20E-05 / 4.53	1.94E-04 / 7.37	3.56E-04 / 10.56
LPSI and CSS Pumps FR	8.90E-05 / 2.1	Weibull	burn-in failures excluded	5.91E-05 / 2.4	1.38E-04 / 2.49	2.26E-04 / 4.32	3.21E-04 / 6,72
CCS Pumps FD	3.60E-05 / 4.2	log-liner		3.85E-05 / 2.29	8.25E-05 / 17.31	1.77E-04 / 206.4	3.78E-04 / 2540
CSS MOVs FO	6.80E-04 / 1.4	Weibull	burn-in failures excluded	7.59E-04 / 1.95	1.49E-03 / 5.09	2.21E-03 / 10.02	2.92E-03 / 16.38
LPSI MOVs FD	1.10E-04 / 1.5	log-linear	-	9.92E-05 / 1.71	1.36E-04 / 2.30	1.86E-04 / 5.36	2.54E-04 / 13.23

Annexe 5 : CSS quantitative analysis results for time-dependent model

Table A5.1. MCS for unit age 10 years

№	MCS	Fract. Contr. to Q_t, %	BE 1	BE 2
1	1.50E-04	19.93	HE_I&C	
2	4.55E-05	6.05	CSS2VBE2RO_10_B-ALL	
3	4.37E-05	5.81	CCFRWSTLS1_10-124	
4	4.37E-05	5.81	CCFRWSTLS1_10-ALL	
5	4.37E-05	5.81	CCFRWSTLS1_10-134	
6	4.37E-05	5.81	CCFRWSTLS1_10-234	
7	4.37E-05	5.81	CCFRWSTLS1_10-123	
8	2.83E-05	3.76	CSS2PO_48H_10_B-ALL	
9	1.75E-05	2.33	CSS2PO#1DS-ALL	
10	1.51E-05	2	RPS2CCF3-ALL	
11	1.00E-05	1.33	SUMP-CSS-LPSI	
12	7.87E-06	1.05	CSS001PO_DF_48H_10_B	CSS002PO_DF_48H_10_B
13	7.40E-06	0.98	CSS4VBE1RO_10_B-ALL	
14	6.03E-06	0.8	RPS4CCF2-13	
15	6.03E-06	0.8	RPS4CCF2-23	
16	6.03E-06	0.8	RPS4CCF2-24	
17	6.03E-06	0.8	RPS4CCF2-14	
18	5.54E-06	0.74	CSS2POJ1DS_10_B-ALL	
19	5.30E-06	0.7	CSS2VBJ2DS-ALL	
20	4.90E-06	0.65	CSS2MO61DF_48H_1-ALL	

Table A5.2. MCS for unit age 20 years

№	MCS	Fract. Contr. to Q_t, %	BE 1	BE 2
1	1.50E-04	12.88	HE_I&C	
2	8.94E-05	7.68	CSS2VBE2RO_20_B-ALL	
3	7.90E-05	6.78	CCFRWSTLS1_20-234	
4	7.90E-05	6.78	CCFRWSTLS1_20-123	
5	7.90E-05	6.78	CCFRWSTLS1_20-124	
6	7.90E-05	6.78	CCFRWSTLS1_20-134	
7	7.90E-05	6.78	CCFRWSTLS1_20-ALL	
8	6.60E-05	5.67	CSS2PO_48H_20_B-ALL	
9	4.27E-05	3.67	CSS001PO_DF_48H_20_B	CSS002PO_DF_48H_20_B
10	1.75E-05	1.5	CSS2PO#1DS-ALL	
11	1.51E-05	1.29	RPS2CCF3-ALL	
12	1.45E-05	1.25	CSS4VBE1RO_20_B-ALL	
13	1.07E-05	0.92	CSS2MO61DS_2-ALL	
14	1.00E-05	0.86	SUMP-CSS-LPSI	
15	9.15E-06	0.79	CSS002PO_DF_48H_20_B	CSS013VB_RO_20_B
16	9.15E-06	0.79	CSS001PO_DF_48H_20_B	CSS014VB_RO_20_B
17	6.89E-06	0.59	CSS2MO61DF_48H_2-ALL	
18	6.48E-06	0.56	CSS2POJ1DS_20_B-ALL	
19	6.03E-06	0.52	RPS4CCF2-24	
20	6.03E-06	0.52	RPS4CCF2-14	

Table A5.3. MCS for unit age 30 years

№	MCS	Fract. Contr. to Q_t, %	BE 1	BE 2
1	1.50E-04	7.5	HE_I&C	
2	1.47E-04	7.35	CSS2MO61DS_3-ALL	
3	1.36E-04	6.81	CCFRWSTLS1_30-134	
4	1.36E-04	6.81	CCFRWSTLS1_30-123	
5	1.36E-04	6.81	CCFRWSTLS1_30-234	
6	1.36E-04	6.81	CCFRWSTLS1_30-124	
7	1.36E-04	6.81	CCFRWSTLS1_30-ALL	
8	1.33E-04	6.63	CSS2VBE2RO_30_B-ALL	
9	1.14E-04	5.71	CSS001PO_DF_48H_30_B	CSS002PO_DF_48H_30_B
10	1.08E-04	5.4	CSS2PO_48H_30_B-ALL	
11	2.98E-05	1.49	CSS001PO_DF_48H_30_B	CSS002MO_DS_3
12	2.98E-05	1.49	CSS001MO_DS_3	CSS002PO_DF_48H_30_B
13	2.22E-05	1.11	CSS002PO_DF_48H_30_B	CSS013VB_RO_30_B
14	2.22E-05	1.11	CSS001PO_DF_48H_30_B	CSS014VB_RO_30_B
15	2.16E-05	1.08	CSS4VBE1RO_30_B-ALL	
16	1.75E-05	0.88	CSS2PO#1DS-ALL	
17	1.51E-05	0.75	RPS2CCF3-ALL	
18	1.00E-05	0.5	SUMP-CSS-LPSI	
19	8.40E-06	0.42	CSS2MO61DF_48H_3-ALL	
20	7.80E-06	0.39	CSS001MO_DS_3	CSS002MO_DS_3

Table A5.4. MCS for unit age 40 years

№	MCS	Fract. Contr. to Q_t, %	BE 1	BE 2
1	2.01E-03	24.53	CSS2MO61DS_4-ALL	
2	1.46E-03	17.8	CSS001MO_DS_4	CSS002MO_DS_4
3	5.78E-04	7.06	CSS001PO_DF_48H_40_B	CSS002MO_DS_4
4	5.78E-04	7.06	CSS001MO_DS_4	CSS002PO_DF_48H_40_B
5	2.34E-04	2.85	CCFRWSTLS1_40-123	
6	2.34E-04	2.85	CCFRWSTLS1_40-134	
7	2.34E-04	2.85	CCFRWSTLS1_40-234	
8	2.34E-04	2.85	CCFRWSTLS1_40-124	
9	2.34E-04	2.85	CCFRWSTLS1_40-ALL	
10	2.29E-04	2.8	CSS001PO_DF_48H_40_B	CSS002PO_DF_48H_40_B
11	1.75E-04	2.14	CSS2VBE2RO_40_B-ALL	
12	1.53E-04	1.87	CSS2PO_48H_40_B-ALL	
13	1.50E-04	1.83	HE_I&C	
14	1.05E-04	1.28	CSS001MO_DS_4	CSS014VB_RO_40_B
15	1.05E-04	1.28	CSS002MO_DS_4	CSS013VB_RO_40_B
16	4.16E-05	0.51	CSS002PO_DF_48H_40_B	CSS013VB_RO_40_B
17	4.16E-05	0.51	CSS001PO_DF_48H_40_B	CSS014VB_RO_40_B
18	2.85E-05	0.35	CSS4VBE1RO_40_B-ALL	
19	1.75E-05	0.21	CSS2PO#1DS-ALL	
20	1.51E-05	0.18	RPS2CCF3-ALL	

Table A5.5. BE Importance measures for unit age 10 years

№	BE	Q(t)	FC	RDF	RIF	Sensitivity
1	HE_I&C	1.50E-04	2.00E-01	1.25E+00	1.33E+03	3.41E+00
2	CSS2VBE2RO_10_B-ALL	4.55E-05	6.06E-02	1.06E+00	1.33E+03	1.63E+00
3	CCFRWSTLS1_10-234	4.37E-05	5.81E-02	1.06E+00	1.33E+03	1.61E+00
4	CCFRWSTLS1_10-ALL	4.37E-05	5.81E-02	1.06E+00	1.33E+03	1.61E+00
5	CCFRWSTLS1_10-123	4.37E-05	5.81E-02	1.06E+00	1.33E+03	1.61E+00
6	CCFRWSTLS1_10-124	4.37E-05	5.81E-02	1.06E+00	1.33E+03	1.61E+00
7	CCFRWSTLS1_10-134	4.37E-05	5.81E-02	1.06E+00	1.33E+03	1.61E+00
8	CSS001PO_DF_48H_10_B	2.80E-03	3.88E-02	1.04E+00	1.47E+01	1.40E+00
9	CSS2PO_48H_10_B-ALL	2.83E-05	3.77E-02	1.04E+00	1.33E+03	1.39E+00
10	CSS002PO_DF_48H_10_B	2.80E-03	3.66E-02	1.04E+00	1.39E+01	1.37E+00

Table A5.6. BE Importance measures for unit age 20 years

№	BE	Q(t)	FC	RDF	RIF	Sensitivity
1	HE_I&C	1.50E-04	1.29E-01	1.15E+00	8.60E+02	2.44E+00
2	CSS001PO_DF_48H_20_B	6.54E-03	8.48E-02	1.09E+00	1.38E+01	1.90E+00
3	CSS002PO_DF_48H_20_B	6.54E-03	8.15E-02	1.09E+00	1.33E+01	1.87E+00
4	CSS2VBE2RO_20_B-ALL	8.94E-05	7.69E-02	1.08E+00	8.60E+02	1.82E+00
5	CCFRWSTLS1_20-134	7.90E-05	6.79E-02	1.07E+00	8.60E+02	1.72E+00
6	CCFRWSTLS1_20-234	7.90E-05	6.79E-02	1.07E+00	8.60E+02	1.72E+00
7	CCFRWSTLS1_20-ALL	7.90E-05	6.79E-02	1.07E+00	8.60E+02	1.72E+00
8	CCFRWSTLS1_20-123	7.90E-05	6.79E-02	1.07E+00	8.60E+02	1.72E+00
9	CCFRWSTLS1_20-124	7.90E-05	6.79E-02	1.07E+00	8.60E+02	1.72E+00
10	CSS2PO_48H_20_B-ALL	6.60E-05	5.68E-02	1.06E+00	8.60E+02	1.59E+00

Table A5.7. BE Importance measures for unit age 30 years

№	BE	Q(t)	FC	RDF	RIF	Sensitivity
1	CSS001PO_DF_48H_30_B	1.07E-02	1.21E-01	1.14E+00	1.20E+01	2.33E+00
2	CSS002PO_DF_48H_30_B	1.07E-02	1.18E-01	1.13E+00	1.18E+01	2.29E+00
3	HE_I&C	1.50E-04	7.51E-02	1.08E+00	5.01E+02	1.80E+00
4	CSS2MO61DS_3-ALL	1.47E-04	7.36E-02	1.08E+00	5.01E+02	1.78E+00
5	CCFRWSTLS1_30-123	1.36E-04	6.82E-02	1.07E+00	5.01E+02	1.72E+00
6	CCFRWSTLS1_30-234	1.36E-04	6.82E-02	1.07E+00	5.01E+02	1.72E+00
7	CCFRWSTLS1_30-124	1.36E-04	6.82E-02	1.07E+00	5.01E+02	1.72E+00
8	CCFRWSTLS1_30-134	1.36E-04	6.82E-02	1.07E+00	5.01E+02	1.72E+00
9	CCFRWSTLS1_30-ALL	1.36E-04	6.82E-02	1.07E+00	5.01E+02	1.72E+00
10	CSS2VBE2RO_30_B-ALL	1.33E-04	6.64E-02	1.07E+00	5.01E+02	1.70E+00

Table A5.8. BE Importance measures for unit age 40 years

№	BE	Q(t)	FC	RDF	RIF	Sensitivity
1	CSS001MO_DS_4	3.82E-02	3.01E-01	1.41E+00	8.34E+00	4.93E+00
2	CSS002MO_DS_4	3.82E-02	2.97E-01	1.41E+00	8.26E+00	4.88E+00
3	CSS2MO61DS_4-ALL	2.01E-03	2.46E-01	1.32E+00	1.22E+02	4.10E+00
4	CSS001PO_DF_48H_40_B	1.51E-02	1.19E-01	1.13E+00	8.34E+00	2.25E+00
5	CSS002PO_DF_48H_40_B	1.51E-02	1.18E-01	1.13E+00	8.26E+00	2.23E+00
6	CCFRWSTLS1_40-123	2.34E-04	2.86E-02	1.03E+00	1.22E+02	1.29E+00
7	CCFRWSTLS1_40-ALL	2.34E-04	2.86E-02	1.03E+00	1.22E+02	1.29E+00
8	CCFRWSTLS1_40-234	2.34E-04	2.86E-02	1.03E+00	1.22E+02	1.29E+00
9	CCFRWSTLS1_40-124	2.34E-04	2.86E-02	1.03E+00	1.22E+02	1.29E+00
10	CCFRWSTLS1_40-134	2.34E-04	2.86E-02	1.03E+00	1.22E+02	1.29E+00

Table A5.9. CSS components importance measures for unit age 10 years

№	Component	FC	RDF	RIF	Sensitivity
1	CSS002PO	1.11E-01	1.12E+00	1.33E+03	2.22E+00
2	CSS013VB	8.65E-02	1.09E+00	1.33E+03	1.93E+00
3	CSS014VB	8.54E-02	1.09E+00	1.33E+03	1.92E+00
4	CSS001PO	3.70E-02	1.04E+00	1.33E+03	1.38E+00
5	RPS073UA	2.40E-02	1.02E+00	1.33E+03	1.24E+00
6	RPS073UB	2.38E-02	1.02E+00	1.33E+03	1.24E+00
7	CSS009VB	1.27E-02	1.01E+00	1.33E+03	1.13E+00
8	CSS007VB	1.27E-02	1.01E+00	1.33E+03	1.13E+00
9	CSS010VB	1.27E-02	1.01E+00	1.33E+03	1.13E+00
10	CSS008VB	1.27E-02	1.01E+00	1.33E+03	1.13E+00

Table A5.10. CSS components importance measures for unit age 20 years

№	Component	FC	RDF	RIF	Sensitivity
1	CSS002PO	1.63E-01	1.20E+00	8.60E+02	2.89E+00
2	CSS013VB	1.08E-01	1.12E+00	8.60E+02	2.18E+00
3	CSS014VB	1.07E-01	1.12E+00	8.60E+02	2.17E+00
4	CSS001PO	2.56E-02	1.03E+00	8.60E+02	1.26E+00
5	RPS073UA	1.67E-02	1.02E+00	8.60E+02	1.17E+00
6	RPS073UB	1.65E-02	1.02E+00	8.60E+02	1.17E+00
7	CSS009VB	1.52E-02	1.02E+00	8.60E+02	1.15E+00
8	CSS007VB	1.52E-02	1.02E+00	8.60E+02	1.15E+00
9	CSS010VB	1.51E-02	1.02E+00	8.60E+02	1.15E+00
10	CSS008VB	1.51E-02	1.02E+00	8.60E+02	1.15E+00

Table A5.11. CSS components importance measures for unit age 30 years

№	Component	FC	RDF	RIF	Sensitivity
1	CSS002PO	1.87E-01	1.23E+00	5.01E+02	3.22E+00
2	CSS013VB	9.94E-02	1.11E+00	5.01E+02	2.08E+00
3	CSS014VB	9.87E-02	1.11E+00	5.01E+02	2.07E+00
4	CSS001PO	1.64E-02	1.02E+00	5.01E+02	1.16E+00
5	CSS009VB	1.33E-02	1.01E+00	5.01E+02	1.13E+00
6	CSS007VB	1.33E-02	1.01E+00	5.01E+02	1.13E+00
7	CSS010VB	1.32E-02	1.01E+00	5.01E+02	1.13E+00
8	CSS008VB	1.32E-02	1.01E+00	5.01E+02	1.13E+00
9	RPS073UA	1.08E-02	1.01E+00	5.01E+02	1.11E+00
10	RPS073UB	1.07E-02	1.01E+00	5.01E+02	1.11E+00

Table A5.12. CSS components importance measures for unit age 40 years

№	Component	FC	RDF	RIF	Sensitivity
1	CSS002PO	1.37E-01	1.16E+00	1.22E+02	2.54E+00
2	CSS013VB	4.73E-02	1.05E+00	1.22E+02	1.49E+00
3	CSS014VB	4.70E-02	1.05E+00	1.22E+02	1.48E+00
4	CSS001PO	5.97E-03	1.01E+00	1.22E+02	1.06E+00
5	CSS007VB	5.14E-03	1.01E+00	1.22E+02	1.05E+00
6	CSS009VB	5.14E-03	1.01E+00	1.22E+02	1.05E+00
7	CSS010VB	5.13E-03	1.01E+00	1.22E+02	1.05E+00
8	CSS008VB	5.13E-03	1.01E+00	1.22E+02	1.05E+00
9	RPS073UA	4.06E-03	1.00E+00	1.22E+02	1.04E+00
10	RPS073UB	4.03E-03	1.00E+00	1.22E+02	1.04E+00

Annexe 6 : Large LOCA time-dependent model results (accident sequences CDF, MCS and importance measures)

Table 6.1. MCS for unit age of 10 years

№	MCS value	MCS contributiont o the CDF, %	BE 1	BE 2	BE 3	BE 4	BE 5
1	7.53E-09	11.4	CL-LOCA	LLOCA	IE-PO	RPC122VP_RO	
2	7.53E-09	11.4	CL-LOCA	LLOCA	IE-PO	RPC222VP_RO	
3	3.62E-09	5.48	CL-LOCA	HE_I&C	LLOCA	IE-PO	
4	3.42E-09	5.17	CL-LOCA	LLOCA	IE-PO	RSI2PO_48H_10_B-ALL	
5	2.41E-09	3.65	HL-LOCA	HE_I&C	LLOCA	IE-PO	
6	2.28E-09	3.45	HL-LOCA	LLOCA	IE-PO	RSI2PO_48H_10_B-ALL	
7	1.10E-09	1.66	CL-LOCA	CSS2VBE2RO_10_B-ALL	LLOCA	IE-PO	
8	1.06E-09	1.6	CL-LOCA	CCFRWSTLS1_10-234	LLOCA	IE-PO	

9	1.06E-09	1.6	CL-LOCA	CCFRWSTLS1_10-134	LLOCA	IE-PO	
10	1.06E-09	1.6	CL-LOCA	CCFRWSTLS1_10-124	LLOCA	IE-PO	
11	1.06E-09	1.6	CL-LOCA	CCFRWSTLS1_10-123	LLOCA	IE-PO	
12	1.06E-09	1.6	CL-LOCA	CCFRWSTLS1_10-ALL	LLOCA	IE-PO	
13	7.33E-10	1.11	HL-LOCA	CSS2VBE2RO_10_B-ALL	LLOCA	IE-PO	
14	7.03E-10	1.06	HL-LOCA	CCFRWSTLS1_10-ALL	LLOCA	IE-PO	
15	7.03E-10	1.06	HL-LOCA	CCFRWSTLS1_10-134	LLOCA	IE-PO	
16	7.03E-10	1.06	HL-LOCA	CCFRWSTLS1_10-123	LLOCA	IE-PO	
17	7.03E-10	1.06	HL-LOCA	CCFRWSTLS1_10-234	LLOCA	IE-PO	

18	7.03E-10	1.06	HL-LOCA	CCFRWSTLS1_10-124	LLOCA	IE-PO	
19	6.84E-10	1.03	CL-LOCA	CSS2PO_48H_10_B-ALL	LLOCA	IE-PO	

Table A6.2. MCS for unit age of 20 years

№	MCS value	MCS contribution to the CDF, %	BE 1	BE 2	BE 3	BE 4	BE 5
1	7.97E-09	8.36	CL-LOCA	LLOCA	IE-PO	RSI2PO_48H_20_B-ALL	
2	7.53E-09	7.91	CL-LOCA	LLOCA	IE-PO	RPC222VP_RO	
3	7.53E-09	7.91	CL-LOCA	LLOCA	IE-PO	RPC122VP_RO	
4	5.31E-09	5.58	HL-LOCA	LLOCA	IE-PO	RSI2PO_48H_20_B-ALL	
5	3.62E-09	3.8	CL-LOCA	HE_I&C	LLOCA	IE-PO	
6	2.41E-09	2.53	HL-LOCA	HE_I&C	LLOCA	IE-PO	
7	2.16E-09	2.26	CL-LOCA	CSS2VBE2RO_20_B-ALL	LLOCA	IE-PO	
8	1.91E-09	2	CL-LOCA	CCFRWSTLS1_20-234	LLOCA	IE-PO	
9	1.91E-09	2	CL-LOCA	CCFRWSTLS1_2	LLOCA	IE-PO	

				0-ALL			
10	1.91E-09	2	CL-LOCA	CCFRWSTLS1_20-134	LLOCA	IE-PO	
11	1.91E-09	2	CL-LOCA	CCFRWSTLS1_20-123	LLOCA	IE-PO	
12	1.91E-09	2	CL-LOCA	CCFRWSTLS1_20-124	LLOCA	IE-PO	
13	1.59E-09	1.67	CL-LOCA	CSS2PO_48H_20_B-ALL	LLOCA	IE-PO	
14	1.44E-09	1.51	HL-LOCA	CSS2VBE2RO_20_B-ALL	LLOCA	IE-PO	
15	1.27E-09	1.33	HL-LOCA	CCFRWSTLS1_20-124	LLOCA	IE-PO	
16	1.27E-09	1.33	HL-LOCA	CCFRWSTLS1_20-234	LLOCA	IE-PO	
17	1.27E-09	1.33	HL-LOCA	CCFRWSTLS1_20-123	LLOCA	IE-PO	
18	1.27E-09	1.33	HL-LOCA	CCFRWSTLS1_2	LLOCA	IE-PO	

				0-ALL			
19	1.27E-09	1.33	HL-LOCA	CCFRWSTLS1_20-134	LLOCA	IE-PO	
20	1.06E-09	1.12	HL-LOCA	CSS2PO_48H_20_B-ALL	LLOCA	IE-PO	

Table A6.3. MCS for unit age of 30 years

№	MCS value	MCS contribution to the CDF, %	BE 1	BE 2	BE 3	BE 4	BE 5
1	1.30E-08	8.45	CL-LOCA	LLOCA	IE-PO	RSI2PO_48H_30_B-ALL	
2	8.68E-09	5.64	HL-LOCA	LLOCA	IE-PO	RSI2PO_48H_30_B-ALL	
3	7.53E-09	4.89	CL-LOCA	LLOCA	IE-PO	RPC122VP_RO	
4	7.53E-09	4.89	CL-LOCA	LLOCA	IE-PO	RPC222VP_RO	
5	3.62E-09	2.35	CL-LOCA	HE_I&C	LLOCA	IE-PO	

6	3.55E-09	2.3	CL-LOCA	LLOCA	IE-PO	RSI2MO61DS_30_B-ALL	
7	3.55E-09	2.3	CL-LOCA	CSS2MO61DS_3-ALL	LLOCA	IE-PO	
8	3.29E-09	2.13	CL-LOCA	CCFRWSTLS1_30-ALL	LLOCA	IE-PO	
9	3.29E-09	2.13	CL-LOCA	CCFRWSTLS1_30-234	LLOCA	IE-PO	
10	3.29E-09	2.13	CL-LOCA	CCFRWSTLS1_30-134	LLOCA	IE-PO	
11	3.29E-09	2.13	CL-LOCA	CCFRWSTLS1_30-124	LLOCA	IE-PO	
12	3.29E-09	2.13	CL-LOCA	CCFRWSTLS1_30-123	LLOCA	IE-PO	
13	3.20E-09	2.08	CL-LOCA	CSS2VBE2RO_30_B-ALL	LLOCA	IE-PO	
14	2.75E-09	1.79	CL-LOCA	CSS001PO_DF_48H_30_B	CSS002PO_DF_48H_30_B	LLOCA	IE-PO

15	2.60E-09	1.69	CL-LOCA	CSS2PO_48H_30_B-ALL	LLOCA	IE-PO	
16	2.54E-09	1.65	CL-LOCA	LLOCA	IE-PO	RSI001PO_DF_48H_30_B	RSI002PO_DF_48H_30_B
17	2.41E-09	1.57	HL-LOCA	HE_I&C	LLOCA	IE-PO	
18	2.37E-09	1.54	HL-LOCA	LLOCA	IE-PO	RSI2MO61DS_30_B-ALL	
19	2.37E-09	1.54	HL-LOCA	CSS2MO61DS_3-ALL	LLOCA	IE-PO	
20	2.19E-09	1.42	HL-LOCA	CCFRWSTLS1_30-ALL	LLOCA	IE-PO	

Table A6.4. MCS for unit age of 40 years

№	MCS value	MCS contribution to the CDF, %	BE 1	BE 2	BE 3	BE 4	BE 5
1	4.85E-08	7.59	CL-LOCA	CSS2MO61DS_4-ALL	LLOCA	IE-PO	

2	4.85E-08	7.59	CL-LOCA	LLOCA	IE-PO	RSI2MO61DS_40_B-ALL	
3	3.52E-08	5.51	CL-LOCA	LLOCA	IE-PO	RSI001MO_DS_40_B	RSI002MO_DS_40_B
4	3.52E-08	5.51	CL-LOCA	CSS001MO_DS_4	CSS002MO_DS_4	LLOCA	IE-PO
5	3.23E-08	5.06	HL-LOCA	LLOCA	IE-PO	RSI2MO61DS_40_B-ALL	
6	3.23E-08	5.06	HL-LOCA	CSS2MO61DS_4-ALL	LLOCA	IE-PO	
7	2.35E-08	3.67	HL-LOCA	CSS001MO_DS_4	CSS002MO_DS_4	LLOCA	IE-PO
8	2.35E-08	3.67	HL-LOCA	LLOCA	IE-PO	RSI001MO_DS_40_B	RSI002MO_DS_40_B
9	1.85E-08	2.89	CL-LOCA	LLOCA	IE-PO	RSI2PO_48H_40_B-ALL	
10	1.40E-08	2.18	CL-LOCA	CSS001MO_DS_4	CSS002PO_DF_48H_40_B	LLOCA	IE-PO

11	1.40E-08	2.18	CL-LOCA	CSS001PO_DF_48H_40_B	CSS002MO_DS_4	LLOCA	IE-PO
12	1.34E-08	2.1	CL-LOCA	LLOCA	IE-PO	RSI001MO_DS_40_B	RSI002PO_DF_48H_40_B
13	1.34E-08	2.1	CL-LOCA	LLOCA	IE-PO	RSI001PO_DF_48H_40_B	RSI002MO_DS_40_B
14	1.23E-08	1.93	HL-LOCA	LLOCA	IE-PO	RSI2PO_48H_40_B-ALL	
15	9.30E-09	1.46	HL-LOCA	CSS001MO_DS_4	CSS002PO_DF_48H_40_B	LLOCA	IE-PO
16	9.30E-09	1.46	HL-LOCA	CSS001PO_DF_48H_40_B	CSS002MO_DS_4	LLOCA	IE-PO
17	8.93E-09	1.4	HL-LOCA	LLOCA	IE-PO	RSI001MO_DS_40_B	RSI002PO_DF_48H_40_B
18	8.93E-09	1.4	HL-LOCA	LLOCA	IE-PO	RSI001PO_DF_48H_40_B	RSI002MO_DS_40_B
19	7.53E-09	1.18	CL-LOCA	LLOCA	IE-PO	RPC222VP_RO	
20	7.53E-09	1.18	CL-LOCA	LLOCA	IE-PO	RPC122VP_RO	

Table A6.5. BE’s Importance measures calculated for unit age of 10 years

№	BE	Unavailability	FC	RDF	RIF
21	IE-HS	1.79E-06	1.49E-02	1.02E+00	8.30E+03
8	HE_I&C	1.50E-04	9.23E-02	1.10E+00	6.17E+02
9	RSI2PO_48H_10_B-ALL	1.42E-04	8.72E-02	1.10E+00	6.17E+02
10	CSS2VBE2RO_10_B-ALL	4.55E-05	2.80E-02	1.03E+00	6.17E+02
11	CCFRWSTLS1_10-123	4.37E-05	2.69E-02	1.03E+00	6.17E+02
12	CCFRWSTLS1_10-134	4.37E-05	2.69E-02	1.03E+00	6.17E+02
13	CCFRWSTLS1_10-124	4.37E-05	2.69E-02	1.03E+00	6.17E+02
14	CCFRWSTLS1_10-ALL	4.37E-05	2.69E-02	1.03E+00	6.17E+02
15	CCFRWSTLS1_10-234	4.37E-05	2.69E-02	1.03E+00	6.17E+02
18	CSS2PO_48H_10_B-ALL	2.83E-05	1.74E-02	1.02E+00	6.17E+02

Table A6.6. BE’s Importance measures calculated for unit age of 20 years

№	BE	Unavailability	FC	RDF	RIF
6	RSI2PO_48H_20_B-ALL	3.30E-04	1.41E-01	1.16E+00	4.28E+02
7	RPC122VP_RO	3.12E-04	8.00E-02	1.09E+00	2.57E+02
8	RPC222VP_RO	3.12E-04	8.00E-02	1.09E+00	2.57E+02
9	HE_I&C	1.50E-04	6.40E-02	1.07E+00	4.28E+02
10	CSS001PO_DF_48H_20_B	6.54E-03	4.30E-02	1.04E+00	7.54E+00
11	CSS002PO_DF_48H_20_B	6.54E-03	4.14E-02	1.04E+00	7.29E+00

12	CSS2VBE2RO_20_B-ALL	8.94E-05	3.82E-02	1.04E+00	4.28E+02
13	RSI002PO_DF_48H_20_B	6.27E-03	3.63E-02	1.04E+00	6.76E+00
14	RSI001PO_DF_48H_20_B	6.27E-03	3.63E-02	1.04E+00	6.75E+00
15	CCFRWSTLS1_20-134	7.90E-05	3.37E-02	1.03E+00	4.28E+02

Table A6.7. BE's Importance measures calculated for unit age of 30 years

№	BE	Unavailability	FC	RDF	RIF
6	RSI2PO_48H_30_B-ALL	5.39E-04	1.42E-01	1.17E+00	2.65E+02
7	CSS001PO_DF_48H_30_B	1.07E-02	6.51E-02	1.07E+00	7.03E+00
8	CSS002PO_DF_48H_30_B	1.07E-02	6.36E-02	1.07E+00	6.89E+00
9	RSI002PO_DF_48H_30_B	1.02E-02	5.50E-02	1.06E+00	6.31E+00
10	RSI001PO_DF_48H_30_B	1.02E-02	5.50E-02	1.06E+00	6.31E+00
11	RPC222VP_RO	3.12E-04	4.95E-02	1.05E+00	1.59E+02
12	RPC122VP_RO	3.12E-04	4.95E-02	1.05E+00	1.59E+02
13	HE_I&C	1.50E-04	3.96E-02	1.04E+00	2.65E+02
14	CSS2MO61DS_3-ALL	1.47E-04	3.88E-02	1.04E+00	2.65E+02
15	RSI2MO61DS_30_B-ALL	1.47E-04	3.88E-02	1.04E+00	2.65E+02

Table A6.8. BE's Importance measures calculated for unit age of 40 years

№	BE	Unavailabil	FC	RDF	RIF

		ity			
28	IE-HS	1.79E-06	1.16E-02	1.01E+00	6.46E+03
19	CCFRWSTLS1_40-ALL	2.34E-04	1.49E-02	1.02E+00	6.47E+01
20	CCFRWSTLS1_40-234	2.34E-04	1.49E-02	1.02E+00	6.47E+01
21	CCFRWSTLS1_40-134	2.34E-04	1.49E-02	1.02E+00	6.47E+01
22	CCFRWSTLS1_40-124	2.34E-04	1.49E-02	1.02E+00	6.47E+01
23	CCFRWSTLS1_40-123	2.34E-04	1.49E-02	1.02E+00	6.47E+01
29	CSS2VBE2RO_40_B-ALL	1.75E-04	1.12E-02	1.01E+00	6.47E+01
30	CSS2PO_48H_40_B-ALL	1.53E-04	9.73E-03	1.01E+00	6.47E+01
31	HE_I&C	1.50E-04	9.55E-03	1.01E+00	6.47E+01
47	CSS4VBE1RO_40_B-ALL	2.85E-05	1.81E-03	1.00E+00	6.47E+01

Table A6.9. Component's importance measures calculated for unit age of 10 years

№	Component	FC	RDF	RIF
1	RWST019MN	1.11E-01	1.12E+00	4.33E+03
2	RWST020MN	1.11E-01	1.12E+00	4.33E+03
3	RWST017MN	1.11E-01	1.12E+00	4.33E+03
4	RWST018MN	1.11E-01	1.12E+00	4.33E+03
5	CSS001PO	4.91E-02	1.05E+00	1.26E+03
6	CSS002PO	4.79E-02	1.05E+00	1.26E+03
7	CSS013VB	3.28E-02	1.03E+00	1.86E+03
8	CSS014VB	3.25E-02	1.03E+00	1.86E+03
9	RPS073UA	1.12E-02	1.01E+00	6.23E+02
10	RPS073UB	1.11E-02	1.01E+00	6.23E+02

Table A6.10. Component's importance measures calculated for unit age of 20 years

№	Component	FC	RDF	RIF
1	RWST019MN	1.41E-01	1.16E+00	3.02E+03
2	RWST020MN	1.41E-01	1.16E+00	3.02E+03
3	RWST017MN	1.41E-01	1.16E+00	3.02E+03
4	RWST018MN	1.41E-01	1.16E+00	3.02E+03
5	CSS001PO	8.11E-02	1.09E+00	8.81E+02
6	CSS002PO	7.94E-02	1.09E+00	8.80E+02
7	CSS013VB	4.74E-02	1.05E+00	1.29E+03
8	CSS014VB	4.71E-02	1.05E+00	1.29E+03
9	CSS001MO	9.71E-03	1.01E+00	8.68E+02
10	CSS002MO	9.63E-03	1.01E+00	8.68E+02

Table A6.11. Component’s importance measures calculated for unit age of 30 years

№	Component	FC	RDF	RIF
1	RWST017MN	1.55E-01	1.18E+00	1.87E+03
2	RWST018MN	1.55E-01	1.18E+00	1.87E+03
3	RWST019MN	1.55E-01	1.18E+00	1.87E+03
4	RWST020MN	1.55E-01	1.18E+00	1.87E+03
5	CSS001PO	1.00E-01	1.11E+00	5.53E+02
6	CSS002PO	9.89E-02	1.11E+00	5.53E+02
7	CSS001MO	5.90E-02	1.06E+00	5.41E+02
8	CSS002MO	5.86E-02	1.06E+00	5.41E+02
9	CSS013VB	4.77E-02	1.05E+00	8.05E+02
10	CSS014VB	4.74E-02	1.05E+00	8.05E+02

Table A6.12. Component’s importance measures calculated for unit age of 40 years

№	Component	FC	RDF	RIF
1	CSS001MO	2.94E-01	1.42E+00	1.37E+02
2	CSS002MO	2.92E-01	1.41E+00	1.37E+02
3	CSS001PO	7.76E-02	1.08E+00	1.45E+02
4	CSS002PO	7.67E-02	1.08E+00	1.45E+02
5	RWST020MN	6.81E-02	1.07E+00	4.56E+02
6	RWST017MN	6.81E-02	1.07E+00	4.56E+02
7	RWST018MN	6.81E-02	1.07E+00	4.56E+02
8	RWST019MN	6.81E-02	1.07E+00	4.56E+02
9	CSS013VB	2.30E-02	1.02E+00	2.01E+02
10	CSS014VB	2.28E-02	1.02E+00	2.00E+02

Annexe 7 : Uncertainty analysis results

Table A7.1. Base case

ID	Calc.type	Mean	Median	95th perc.	5th perc.
CD	Reference	7.21E-08	2.38E-08	3.08E-07	2.78E-09
CD_10	10 years	6.61E-08	2.01E-08	2.55E-07	1.77E-09
CD_20	20 years	9.53E-08	3.23E-08	3.81E-07	3.13E-09
CD_30	30 years	1.54E-07	4.91E-08	6.38E-07	3.49E-09
CD_40	40 years	6.39E-07	6.29E-08	8.92E-07	5.14E-09

Table A7.2. Sensitivity study

ID	Calc.type	Mean	Median	95th perc.	5th perc.
CD	Reference	7.21E-08	2.38E-08	3.08E-07	2.78E-09
CD_10	10 years	6.61E-08	2.19E-08	2.48E-07	2.14E-09
CD_20	20 years	9.44E-08	3.24E-08	3.43E-07	3.06E-09
CD_30	30 years	1.34E-07	4.71E-08	5.49E-07	3.76E-09
CD_40	40 years	1.93E-07	6.67E-08	9.36E-07	5.23E-09

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Abstract
This report presents the results of a case study on incorporation of ageing effects into the PSA model and discussions on the use of PSA to evaluate the SSC ageing effect on overall plant safety. The study was carried out within the framework of the EC-JRC Ageing PSA Network Task 7.
The possible impact of age-related degradation on the component reliability and on the plant risk profile is demonstrated using the PWR Large LOCA PSA model as an example. Practical insights, recommendations and limitations are also discussed.

Key Words: ageing effects, Probabilistic Safety Assessment, time-dependent reliability model.